Biomechanical Simulation of the Outcomes of Reduction Aortoplasty Surgery in Patients Eligible for Aortic Valve Replacement: A Case Study of Referrals to Hazrat Rasul Akram Hospital During 1402–1403

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Abstract:

Background and Objective: Aortic surgeries are among the most complex and critical procedures in cardiology and vascular surgery. Reducible aortoplasty offers a viable alternative to ascending aorta grafting for patients with moderate aortic dilation. This study aims to evaluate the hemodynamic effects of reducible aortoplasty and compare clinical outcomes with predictions derived from numerical simulations.

Materials & Methods: A retrospective analysis was performed on data from four patients who underwent reducible aortoplasty. Blood pressure measurements were recorded both preoperatively and postoperatively. To assess hemodynamic changes, we utilized echocardiography, supplemented by finite element modeling (FEM) and numerical simulations. The patients' radiological data were analyzed using Abaqus software in conjunction with the finite element method.

Results: In Case 1, involving a 56-year-old male, minimal alterations in blood pressure were observed post-surgery, with simulation predictions closely aligning with echocardiographic findings. Case 2 involved a 62-year-old male who exhibited a significant postoperative reduction in blood pressure, corroborated by the computational model's results. Case 3, a 75-year-old female, developed aortic valve failure following surgery, an outcome inconsistent with the numerical predictions. In Case 4, a 70-year-old male showed a substantial postoperative decrease in blood pressure, consistent with simulation predictions.

Conclusion: The findings of this study highlight the efficacy of FEM and numerical simulations in evaluating surgical outcomes. However, to enhance the accuracy and reliability of these predictions, it is essential to address current limitations. Improving numerical models to incorporate individualized patient characteristics, providing advanced training for healthcare professionals in modeling techniques, and conducting further investigations may contribute to improved clinical outcomes for patients undergoing aortic surgeries.

Keywords: Reducible aortoplasty, aortic aneurysm, hemodynamics, numerical simulation, finite element method, cardiovascular surgery

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Background and Objective

Reduction aortoplasty is an innovative open-heart surgical technique that offers a viable alternative to ascending aortic grafting using synthetic materials. This procedure is particularly beneficial for patients with moderate aortic dilation that does not involve the aortic root and for those who require a reduction in cross-clamp time.[1,2] Typically performed alongside aortic valve replacement, reduction aortoplasty shows significant promise in improving patient outcomes in several key aspects. First, the procedure can substantially enhance patients' quality of life by replacing a diseased segment of the aorta with a well-fitted prosthesis, thereby enabling greater participation in daily activities. Furthermore, reduction aortoplasty plays a critical role in reducing severe complications associated with aortic diseases, such as angioedema, aneurysms, and aortic rupture.[3,4]

The origins of aortoplasty date back to 1951, when the first aortic replacement surgery using a prosthesis was performed. However, at that time, the lack of advanced surgical techniques and adequate prosthetic options significantly limited its effectiveness. Over the decades, technological advancements and scientific progress have facilitated the development of more refined aortoplasty techniques.[5] The procedure involves excising an oval-shaped segment from the dilated aortic wall through a longitudinal aortotomy. This aortotomy is subsequently closed with a double-layer suture, often reinforced with Teflon strips, to restore the aorta's morphology and achieve its natural diameter. Some researchers suggest that this closure should be completed after assembling the suture line to strengthen the vessel wall and prevent further dilation.[6]

Given the complexity and delicacy inherent in aortic surgery, effective planning and meticulous technical execution are of paramount importance.[7] Biomechanical simulation has emerged as a transformative tool for both preoperative preparation and intraoperative guidance during these procedures. This technology integrates engineering principles and computational methodologies to analyze the mechanics of biological systems. In the context of aortic surgery, biomechanical simulations model aortic behavior under various conditions and assess the impacts of different surgical interventions on aortic function.[8]

One of the notable advantages of biomechanical simulation in aortic surgery is its ability to accurately predict the outcomes of various surgical interventions. By creating a computer model of the aorta and simulating surgical techniques, surgeons can evaluate the potential risks and benefits associated with each approach before the actual procedure. This foresight enables the selection of the most appropriate surgical strategy for each patient, thereby minimizing complications and optimizing surgical outcomes.[9,10]

Moreover, biomechanical simulations can be instrumental during the surgical procedure itself. Surgeons can utilize biomechanical data to refine their approach, ensuring that manipulation of the aorta is performed safely and effectively. This not only reduces the likelihood of intraoperative complications, such as dissection or aortic rupture, but also improves overall surgical success rates.[11]

In addition to its preoperative and intraoperative applications, biomechanical simulation also plays a crucial role in postoperative follow-up. By monitoring changes in aortic function over time, surgeons can evaluate long-term surgical outcomes and make necessary adjustments to optimize patient results. In summary, biomechanical simulation is an invaluable tool in the field of aortic surgery.[8,12] It provides crucial insights into the mechanical stresses and forces acting on the aorta, the effects of surgical interventions, and potential complications that may arise. Consequently, it significantly contributes to enhanced surgical outcomes in aortic procedures. The objective of this study is to perform biomechanical simulations to evaluate the outcomes of reduction aortoplasty in patients undergoing aortic valve replacement.

Materials and Methods

Study Design and Population

This descriptive-analytical study involved four patients who presented to Hazrat Rasoul Akram Hospital between 2023 and 2024 and were considered suitable candidates for reduction aortoplasty combined with aortic valve replacement. The study was approved by the Ethics Committee of Iran University of Medical Sciences (approval code: IR.IUMS.FMD.REC.1403.342), and informed consent was obtained from all participants.

Inclusion Criteria

Patients included in the study met the following criteria:

- Aged 18 years or older
- Ascending aortic diameter ranging from 22 to 55 millimeters (mm), as determined by CT angiography
- Indication for aortic valve replacement due to severe aortic stenosis or regurgitation
- Availability of preoperative CT angiography with a slice thickness of less than 1 mm
- Absence of severe calcification in the aortic wall
- Provision of informed consent to participate in the study

Exclusion Criteria

Patients were excluded from participation in the study if they met any of the following criteria:

- Lack of patient consent for participation
- Diagnosis of a bicuspid aortic valve
- Documented history of connective tissue disorders (e.g., Marfan syndrome, Ehlers-Danlos syndrome)
- Prior history of aortic surgery or intervention
- Presence of uncontrolled chronic illnesses (e.g., diabetes, renal failure)
- Presence of acute or chronic infections
- Poor quality of CT scan images

Data Collection Methods

Imaging: Preoperative CT angiography was performed on all participants utilizing a 64-slice CT scanner (Siemens SOMATOM Definition AS), following established imaging protocols. The imaging specifications were as follows:

- Voltage: 120 kVp
- Current: 300-400 mAs
- Slice thickness: 0.6 mm
- Reconstruction interval: 0.4 mm
- Field of view: 350 mm
- Matrix: 512 × 512 pixels
- Non-ionic contrast agent (Iohexol, 350 mg I/mL) administered at a volume of 80-100 mL

Furthermore, transthoracic echocardiography (TTE) was performed both preoperatively and postoperatively using a Philips EPIQ 7 device equipped with an S5-1 probe. Systolic and diastolic blood pressure measurements were taken with a standard mercury sphygmomanometer before the procedure and again 48 to 72 hours postoperatively.

Image Processing and Geometric Modeling

CT scan images were imported in digital imaging and communications in medicine (DICOM) format into Three-dimensional (3D) Slicer software (version 5.2.2).[13] The image processing steps included:

1. Segmentation: The ascending aorta was isolated from adjacent anatomical structures using a threshold-based segmentation method, with threshold values set between 150 and 400 Hounsfield units.
2. Manual Correction: Segmented boundaries were reviewed and modified as necessary.
3. Smoothing: Image noise was reduced using a Gaussian smoothing filter with a standard deviation of $\sigma = 0.5$.
4. Creation of a 3D Model: A 3D model in STL format was developed from the processed data.

Finite Element Modeling (FEM)

The STL models were subsequently imported into Abaqus/CAE 2022 software, which is designed for finite element analysis (FEA) and computer-aided engineering.[14,15] A specific 3D FEM of the dilated ascending aorta was created for each patient using the following modeling steps:

Meshing Specifications

· Element Type: linear tetrahedral elements (C3D4) used for static analysis

· Meshing Algorithm: advancing front technique

· Number of Elements: ranged from 50,000 to 880,000, depending on geometric complexity

· Number of Nodes: estimated to be between 15,000 and 25,000 nodes

· Mesh Size: 1-2 mm in critical areas and 3-4 mm in less critical regions

· Element Quality Ratio (aspect ratio): less than 3

· Minimum Element Angle: greater than 20 degrees

Mechanical Properties of Materials

The aortic wall was characterized as an isotropic, elastic, and nonlinear material with the following properties:

· Elastic Modulus (E): 2.0 megapascals

· Poisson's Ratio (ν): 0.45

· Density (ρ): 1050 kg/m³

· Wall Thickness: Maintained uniformly at 2 mm across all regions

Boundary Conditions

· Upper end of the aorta (near the arch): fixed in all directions (ENCASTRE)

· Lower end of the aorta (near the valve): permitted to move radially, constrained axially

· Inner surface of the aorta: variable pressure applied over time

Pressure Loading Simulation

The pressure applied to the inner surface of the aorta was modeled based on the patient's measured blood pressure and described using the following sinusoidal function:[18]

· $P(t) = P\_diastolic + (P\_systolic - P\_diastolic) \times \sin^2(\pi t/T)$

Where:

• P(t): pressure at time t (pascals)

• P_systolic: patient's systolic blood pressure (mmHg, converted to Pascals by multiplication with 133.322)

• P_diastolic: patient's diastolic blood pressure (mmHg converted to Pascals by multiplication with 133.322)

• T: duration of one cardiac cycle (0.8 seconds)

Analysis Parameters

· Type of Analysis: dynamic Implicit

· Number of Time Steps: 100 steps per cardiac cycle

· Total Simulation Time: 3 cardiac cycles (total duration: 2.4 seconds)

· Convergence criterion: ($1*10^{-6}$)

Analysis of Results and Parameters Under Review

For each FEM, the following critical parameters were calculated and analyzed:

· Maximum von mises stress within the aortic wall (in megapascals, MPa)

· Pressure distribution on the inner surface of the aorta (in pascals, Pa)

· Radial displacement of the aortic wall (in mm)

· Maximum and minimum principal strains

The safety factor is calculated based on the ultimate tensile strength of the tissue

Table 1- Demographic and clinical characteristics of patients

Case	Age	Gender	Type of surgery	Preoperative aortic diameter (mm)	Preoperative blood pressure (mmHg)	Preoperative pulse
1	56	man	Aortic Root Replacement	48	130.80	85
2	62	man	Ascending Aortic Aneurysm + Coarctation + left anterior descending (LAD) Graft	52	180.110	70
3	75	woman	Aortoplasty + Ascending Aortic Aneurysm	45	110.60	90
4	70	man	Reduction Aortoplasty	50	160.80	80

Model Validation

The simulation outcomes were rigorously compared with results obtained from postoperative echocardiography, using the following criteria for evaluation:

· Measurements of aortic diameter across various regions
· Evaluation of blood flow patterns
· Assessment of aortic valve insufficiency

These validation details have been included to ensure that all necessary information for reproducing the model and its numerical results is accessible to other researchers.

Statistical Analysis

Statistical analyses were performed using SPSS version 26. Quantitative data are presented as mean ± standard deviation, while qualitative data are reported as frequencies and percentages. The Wilcoxon signed-rank test was used to compare preoperative and postoperative results, with a significance level set at $p < 0.05$.

Findings

Demographic Characteristics of Patients

This study involved four patients: three men and one woman. Table 1 presents the demographic and clinical characteristics of the participants.

Results of Modeling and Numerical Simulations

3D FEMs were successfully constructed for all four patients. On average, each model comprised 62,500 ± 12,000 elements and 19,200 ± 3,500 nodes. The mesh quality for all models was deemed acceptable, with a minimum element angle greater than 20 degrees and an aspect ratio less than 3.

Fluid dynamics models were generated for each patient based on preoperative CT scans. Figure 1 illustrates the various aortic valve types (unicuspid, bicuspid, and tricuspid) alongside their corresponding blood flow patterns, using a color spectrum: green to blue indicates a low risk of vascular damage and a minimal probability of blood pressure reduction, while red signifies a high risk of vascular damage and a significant likelihood of unchanged blood pressure postoperatively.

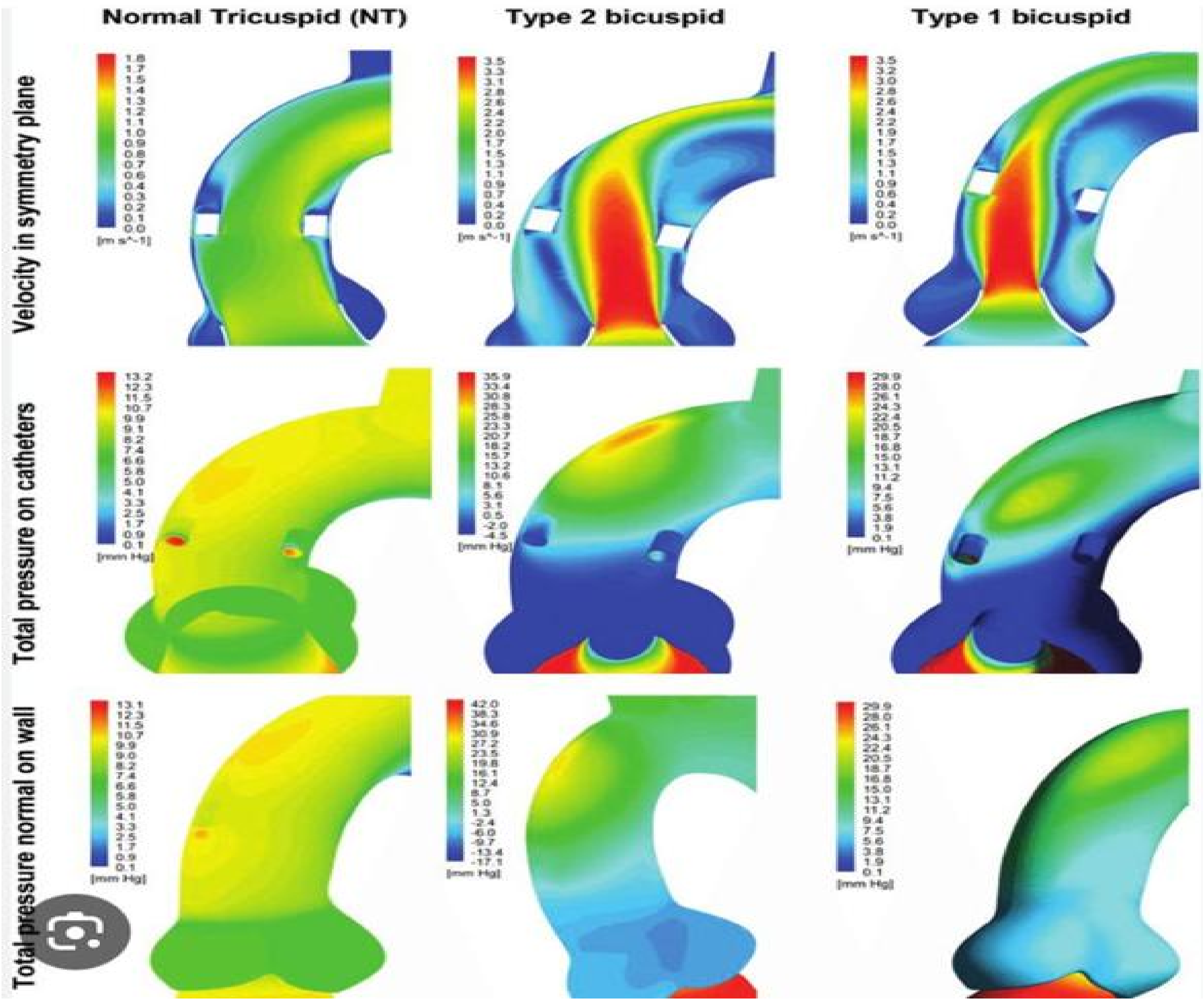

Figure 1 - Comparison of fluid dynamic simulations across different types of aortic valves

Table 2- Numerical simulation results

Case	*Maximum von Mises stress (MPa)*	*Maximum radial displacement (mm)*	*Maximum pressure (kPa)*	*Safety factor*
1	*0.185*	*2.3*	*18.7*	*10.8*
2	*0.220*	*2.8*	*20.7*	*9.1*
3	*0.195*	*2.5*	*21.3*	*10.3*
4	*0.210*	*2.6*	*19.3*	*9.5*

The numerical simulation results for three different types of aortic valves, normal tricuspid, type 2 bicuspid, and type 1 bicuspid, were evaluated based on three critical parameters:

· Top row: velocity measured in the symmetry plane (m/s)

· Middle row: total pressure exerted on the catheters (mmHg)

· Bottom row: total normal pressure applied to the wall (mmHg)

The color spectrum transitions from blue, indicating low pressure and velocity, to red, representing high pressure and velocity. This observation suggests that bicuspid valves produce distinct flow patterns and pressure distributions compared to normal tricuspid valves, which may have implications for surgical planning.

Comparison of Clinical Outcomes Before and After Surgery

Case 1: Aortic Root Replacement in a 56-Year-Old Man

Preoperatively, the patient had an aortic diameter of 48 mm, a systolic blood pressure of 130 mmHg, a diastolic blood pressure of 80 mmHg, and a pulse rate of 85 beats per minute. Postoperative evaluations revealed a systolic blood pressure of 125 mmHg, a diastolic pressure of 80 mmHg, and a pulse rate of 90 beats per minute. Following the root replacement, the aortic diameter decreased to 32 mm, representing a 33% reduction. The changes in blood pressure before and after surgery were minimal.

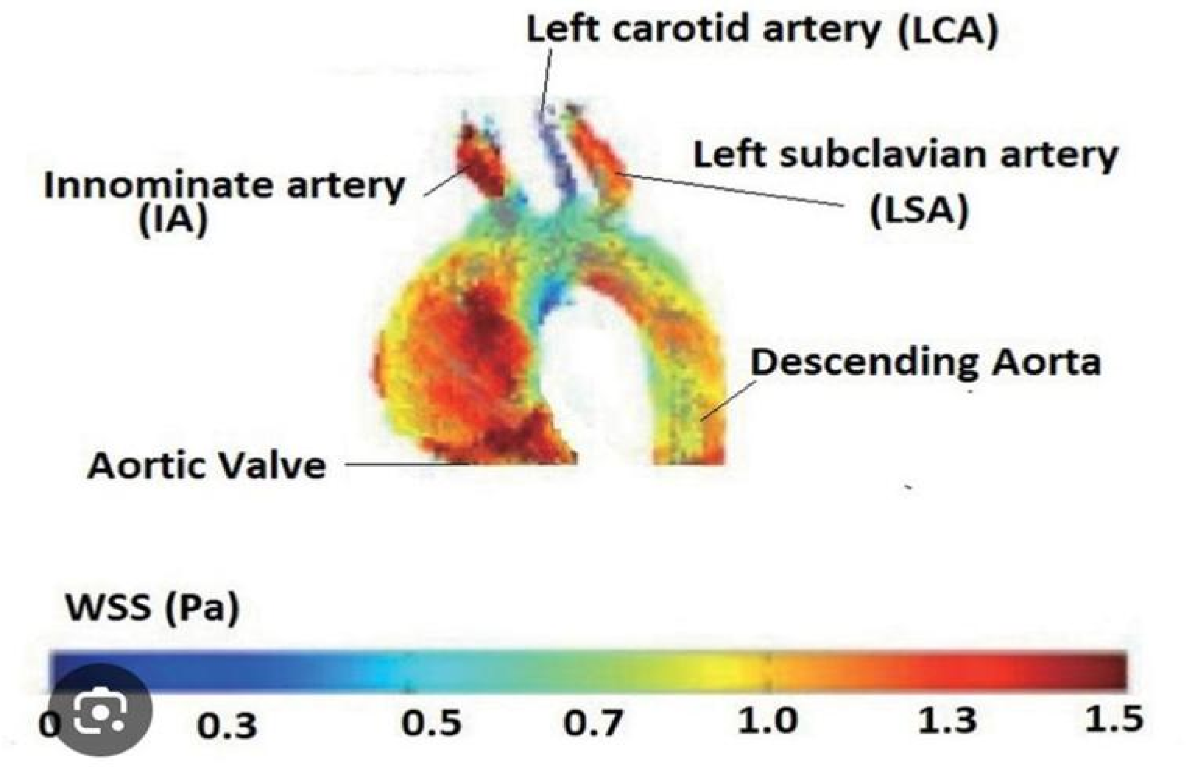

Figure 2 - Blood flow pressure map in the first case - 56-year-old man undergoing aortic root replacement

Simulation results indicated a maximum von mises stress of 0.185 MPa and a maximum radial displacement of 2.3 mm, yielding a safety factor of 10.8. Findings from echocardiography corroborated the numerical simulation predictions regarding aortic dimensions, aortic valve condition, and the integrity of the coronary arteries.

As shown in Figure 2, the aortic valve remained unchanged. The regions expected to exhibit elevated pressure (illustrated in red) within the aortic root, innominate artery (IA; supplying the right arm), and left subclavian artery (LSA; supplying the left arm) were confirmed postoperatively. This finding is consistent with the observation that the patient did not experience reduced pressure levels.

This representation also illustrates the numerical simulation results for the wall shear stress distribution within the aortic arch and its primary branches: the IA, left carotid artery (LCA), LSA, and descending aorta.

The color spectrum indicates shear stress levels, ranging from blue (indicating low shear stress at 0.3 pascals) to red (indicating high shear stress at 1.5 pascals). The areas marked in red at the root of the aorta and its branches, particularly the IA and LSA, exhibit high shear stress levels consistent with the numerical model's predictions. This finding confirms that no significant decrease in blood pressure occurred after surgery.

Clinical observations indicated an improvement in the patient's blood pressure, which decreased from 130/80 mmHg to 125/80 mmHg, aligning closely with the predictions made by the fluid dynamics model.

Case 2: 62-Year-Old Man with Ascending Aortic Aneurysm and Coarctation

A 62-year-old male patient underwent surgical intervention for an ascending aortic aneurysm complicated by stenosis due to coarctation at the junction of the aortic arch and descending aorta, which affected the left anterior descending (LAD) artery. The surgical procedure involved a supracoronary replacement, accompanied by a venous graft to the LAD. Postoperatively, the aortic diameter decreased from 52 mm to 34 mm, representing a 35% reduction. Before surgery, the patient's blood pressure was 180/110 mmHg, with a pulse rate of 70 beats per minute. Postoperative measurements showed improvement to 120/70 mmHg, with a pulse rate of 75 beats per minute, indicating a significant reduction of 60/40 mmHg. Simulation results revealed the highest von mises stress at 220.0 MPa and a maximum radial displacement of 2.8 mm, while the safety factor remained within a safe range of 1.9. These findings demonstrate that, despite the patient's history of resistant hypertension, the surgical procedure resulted in a favorable outcome, as evidenced by the substantial decrease in blood pressure.

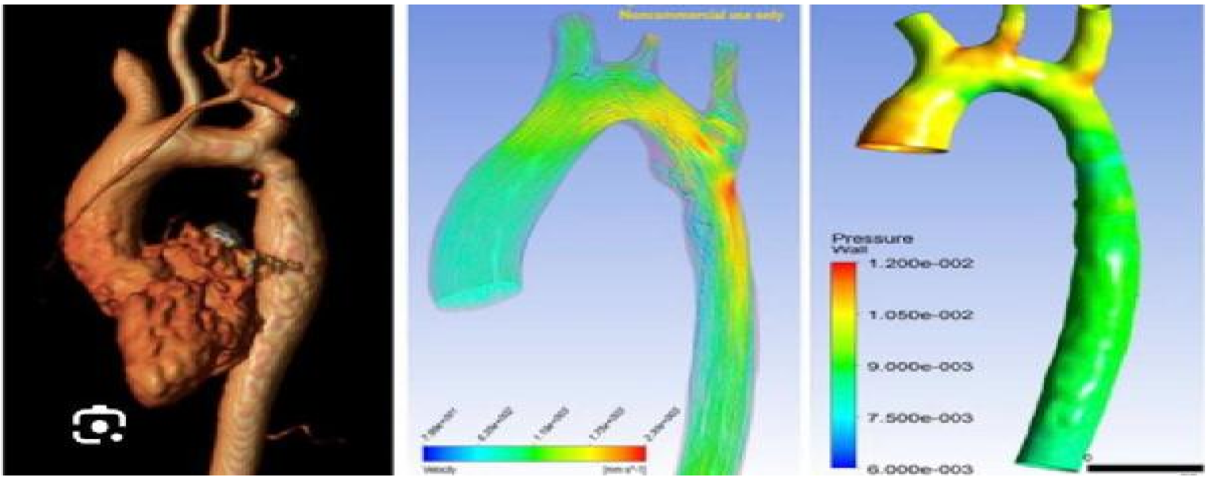

Figure 3 - Comparison of clinical images and numerical simulation in the second case a - 62-year-old man

Notably, contrary to expectations, the fluid dynamics analysis indicated no transition toward the red spectrum (which represents increased velocity and turbulence) despite the dilation of the ascending aorta and the constriction at the coarctation site. Follow-up echocardiograms were fully consistent with the predicted model, as illustrated in Figure 3, which consists of three sections:

Left: A simulated CT scan highlighting an ascending aortic aneurysm and coarctation at the junction of the aortic arch and the descending aorta.

Middle and Right: The pressure distribution in the aortic wall was analyzed using numerical simulations, with a color scale ranging from blue (indicating low pressure of 6.00e-3) to red (indicating high pressure of 1.20e-2).

Important Note: The numerical simulations indicated that, despite the significant dilation of the ascending aorta and the constriction at the coarctation site, the pressure distribution predominantly remained within the green-blue spectrum, representing medium to low pressure, with relatively few regions exhibiting red, which indicates high pressure.

This observation is supported by the patient's clinical outcomes, which reflect a significant reduction in blood pressure postoperatively (from 180/110 mmHg to 120/70 mmHg), consistent with the model's predictions.

Case 3: A 75-Year-Old Woman with Aortoplasty and Ascending Aortic Aneurysm

A 75-year-old female patient from Afghanistan, with no prior history of hypertension, underwent aortoplasty and repair of an ascending aortic aneurysm that initially measured 45 mm in diameter. Postsurgical intervention reduced the aortic diameter to 30 mm, representing a 33% decrease. Her blood pressure changed from 110/60 mmHg with a pulse rate of 90 beats per minute preoperatively to 90/60 mmHg with a pulse rate of 85 beats per minute postoperatively, indicating a systolic reduction of 20 mmHg.

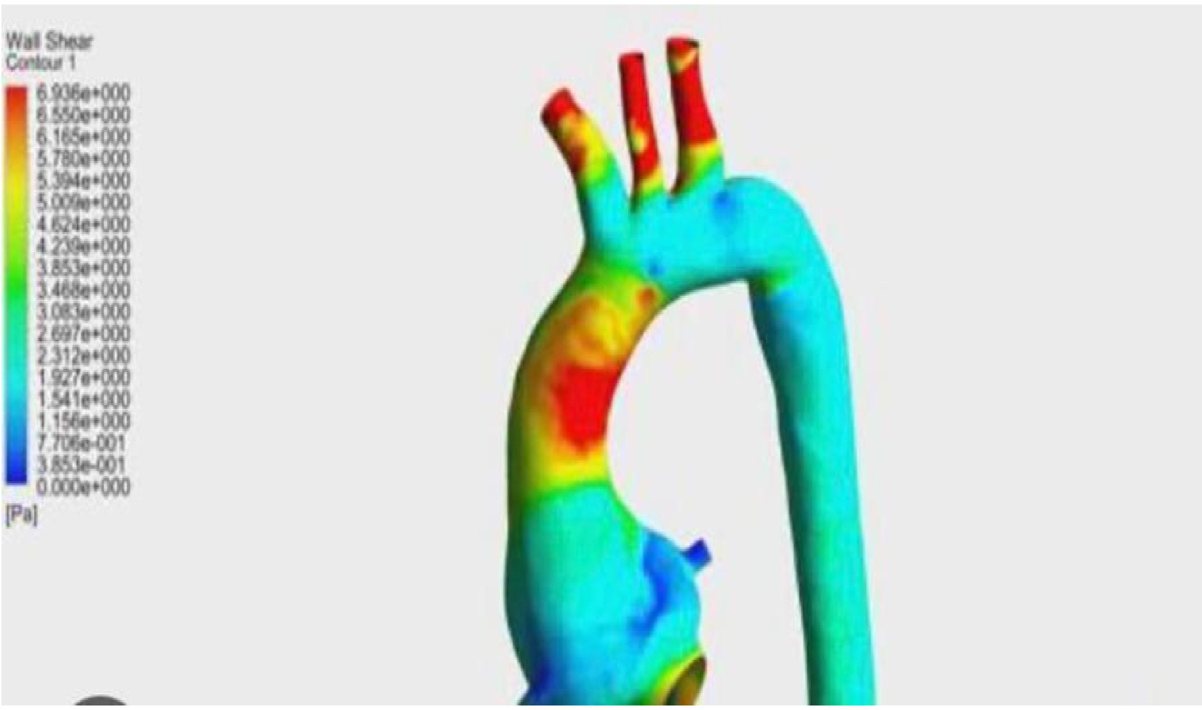

Figure 4- Wall shear stress (WSS) distribution in the third case: a - 75-year-old woman

Simulation results revealed a maximum von mises stress of 0.195 MPa and a maximum radial displacement of 2.5 mm, yielding a safety factor of 10.3. Notably, although the highest recorded pressure in this case was 21.3 kPa, fluid dynamics analyses indicated that most of the arch and descending aorta branches remained within the blue spectrum, suggesting low pressure after surgery, which aligned with clinical findings. However, subsequent echocardiography revealed the emergence of aortic regurgitation, a complication not anticipated in the initial numerical simulations.

Illustrations in this case depict the frictional pressure of blood flow against the vessel wall, with color gradients ranging from blue (indicating zero frictional pressure) to red (indicating a maximum of 6.936 pascals).

Key Observations

· The red regions within the main branches of the aorta, the innominate artery, LCA, and LSA, indicate elevated shear stress.

· The aortic arch and descending aorta predominantly exhibited a blue-green spectrum, indicating medium to low shear stress.

· This observed pressure distribution pattern is consistent with the patient's clinical condition.

Based on the simulation results, it was anticipated that this patient would not experience a significant reduction in blood pressure following surgery. This prediction was confirmed by clinical findings, which showed a change in blood pressure from 140/85 mmHg to 135/80 mmHg.

Case 4: A 70-Year-Old Male Undergoing Reductive Aortoplasty

The patient underwent reductive aortoplasty, initially presenting with an aortic diameter of 50 mm. Preoperatively, the patient exhibited a systolic blood pressure of 160 mmHg, a diastolic blood pressure of 80 mmHg, and a pulse rate of 80 beats per minute. Postoperatively, the aortic diameter decreased to 33 mm, indicating a 34% reduction. Following surgery, the systolic and diastolic pressures were recorded at 130 mmHg and 70 mmHg, respectively, with a pulse rate of 85 beats per minute, indicating a blood pressure reduction of 30/10 mmHg. Simulation data revealed a maximum von Mises stress of 0.210 MPa and a maximum radial displacement of 2.6 mm, resulting in a safety factor of 9.5.

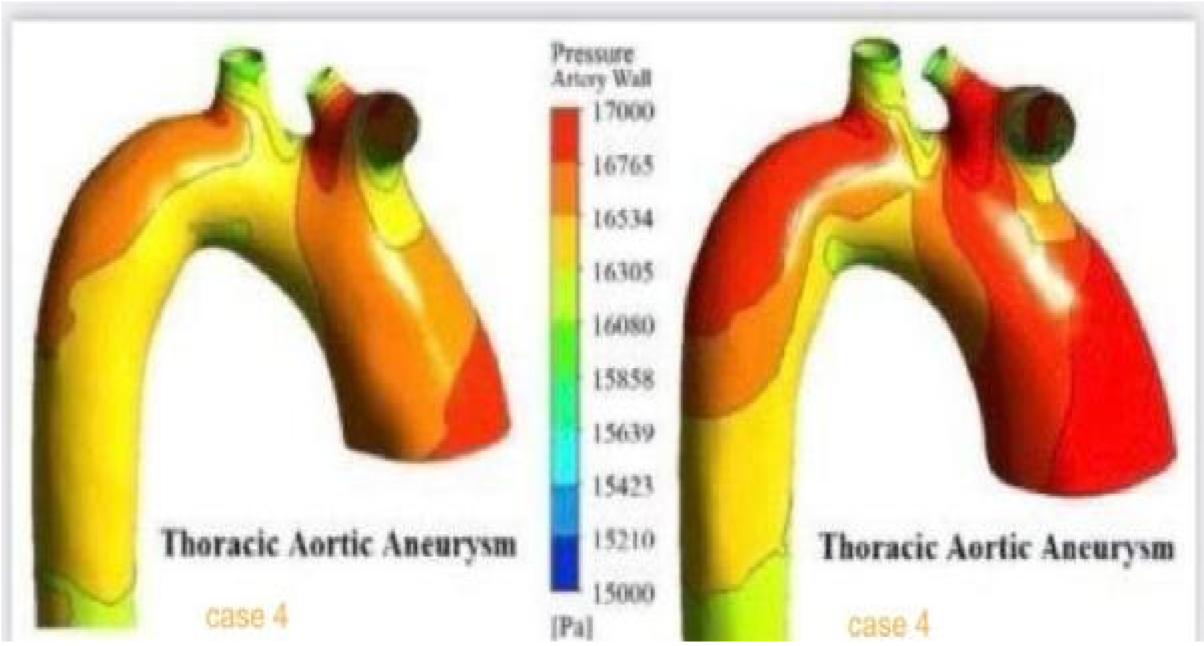

Figure 5- Comparison of arterial wall pressure distribution in case 4 - 70-year-old man

Table 3- Comparison of clinical results before and after surgery

Case	Preoperative aortic diameter (mm)	Postoperative aortic diameter (mm)	Diameter reduction (%)	Preoperative pressure	Postoperative pressure	Pressure change	Preoperative pulse	Postoperative pulse	Model compliance
1	48	32	33%	130.80	125.80	-5.0	85	90	Yes
2	52	34	35%	180.110	120.70	-60.40	70	75	Yes
3	45	30	33%	110.60	90.60	-20.0	90	85	No*
4	50	33	34%	160.80	130.70	-30.10	80	85	Yes

**Disagreement arose due to the occurrence of aortic valve insufficiency, which was not predicted by the model.*

Postoperative echocardiography aligned with the fluid dynamic model, as illustrated in Figure 5, which compares two states of pressure distribution in the aortic wall for this case of thoracic aortic aneurysm.

The left image shows the pressure distribution within the aneurysm region, predominantly in yellow-orange hues, indicating medium to high pressure.

The right image shows increased areas of red, particularly within the aneurysm region and main branches, indicating elevated pressure levels.

Clinical Interpretation: This comparative analysis indicates significant changes in pressure before and after therapeutic intervention or variations in blood flow conditions. The red regions in the right image indicate that the pressure exerted on the aneurysm wall increased under these conditions, potentially elevating the risk of rupture.

Such findings are crucial for assessing the nature and timing of surgical interventions in patients with thoracic aortic aneurysms.

Stress and Pressure Distribution Analysis

The von mises stress distribution analysis revealed that the maximum stresses were concentrated in the curvature of the aorta and at the junction leading to the aortic arch. All cases demonstrated calculated maximum stresses (mean 0.203 ± 0.015 MPa) that were below the ultimate tensile strength of aortic tissue (2 MPa), thereby confirming the safety of the surgical design. Case 2 recorded the highest stress level (0.220 MPa), while Case 1 exhibited the lowest (0.185 MPa).

The maximum radial displacement ranged from 2.3 mm to 2.8 mm, indicating acceptable deformation of the aortic wall. Importantly, the safety factor in all cases exceeded 9, demonstrating a commendable level of surgical safety.

Additionally, the results indicated that following reductive aortoplasty, the blood flow pattern began to normalize, with a marked reduction in regions of stagnant blood.

Analysis of Numerical Simulation Results

The average reduction in aortic diameter across all patients was 33.75%, demonstrating the effectiveness of the surgical interventions in reducing aortic dilation. The most significant decrease in blood pressure was observed in Case 2 (60/40 mmHg), while Case 1 demonstrated minimal change (0.5 mmHg).

Assessment of Model Accuracy

Among the four cases analyzed, three exhibited complete alignment between the numerical simulation results and clinical findings, resulting in a 75% agreement rate. In one instance (Case 3), a discrepancy emerged regarding the onset of aortic valve insufficiency, a complication that was not predicted during the initial modeling process.

Discussion

The impact of aortic surgical procedures on patients' hemodynamic status has garnered significant attention in recent years. Hemodynamics, encompassing the study of blood flow and pressure within the circulatory system, is vital for understanding how alterations in these parameters can influence cardiac function and overall organ health.[19,20] Aortic surgeries may induce both immediate and long-term hemodynamic changes, including fluctuations in blood pressure, changes in heart rate, and variations in blood flow patterns.[21,22]

Research indicates that selecting appropriate surgical techniques, optimizing the timing of the procedure, and ensuring meticulous postoperative management can substantially enhance hemodynamic outcomes. For example, the adoption of minimally invasive approaches, such as endovascular aortic repair (EVAR), has been associated with reduced adverse effects and improved hemodynamic status.[23] Furthermore, continuous monitoring of risk factors, including hypertension and diabetes, both before and after surgical intervention, has been shown to significantly improve patient outcomes.[24,25]

In this study, Cases 1, 2, and 4 demonstrated successful surgical interventions accompanied by corresponding enhancements in hemodynamics. In contrast, Case 3 experienced postoperative complications due to the onset of aortic valve failure. The successful cases showed a strong correlation with predictions derived from FEM and echocardiography, whereas Case 3 deviated from these predictions, resulting in more severe complications.

A comprehensive analysis reveals that numerous factors, including the patient's age, overall health status, and anatomical characteristics, critically influence surgical outcomes. Specifically, Case 3, involving an older patient (45 years old) with a complex surgical scenario, yielded less favorable results. This observation aligns with existing research indicating that age and comorbidities are significant predictors of outcomes in aortic surgeries.[26,27]

Recent validation studies focusing on computational fluid dynamics (CFD) simulations in aortic surgery substantiate the findings of the present study. Girardin et al. (2025), in their comprehensive investigation of patients with aortic dissection, observed that although CFD simulations provide valuable insights into aortic hemodynamics, their predictive accuracy varies depending on patient-specific factors and the complexity of the aortic pathology.[28] Similarly, Ramses and Agu (2025) reported variability in success rates when predicting postoperative outcomes in cases of abdominal aortic aneurysm, highlighting that accuracy is influenced by patient demographics and anatomical intricacies, findings that align with the varied outcomes observed in our case series.[29] Moreover, Catalano et al. (2025), in their comprehensive review of CFD applications in cardiac surgery, emphasized that many CFD studies lack sufficient clinical correlation, resulting in significant disparities in predictive accuracy during validation.[30]

Even in studies reporting less favorable surgical outcomes, patterns similar to those observed in Case 3 of our study have been identified. Bardi (2024), in his doctoral thesis, concluded that although CFD simulations can effectively predict specific hemodynamic parameters, their clinical applicability is often limited by uncontrolled variables, such as tissue remodeling, inflammatory responses, and patient variability.[31] These limitations are evident in the challenges encountered in Case 3, where, despite advanced modeling, the clinical outcomes diverged significantly from the predictions. Furthermore, Loly et al. (2025), in their systematic review of studies published between 2019 and 2024, emphasized that while CFD models possess considerable promise, their clinical implementation necessitates more robust validation against long-term patient outcomes. This supports our observation that CFD predictions may be more reliable for certain patient profiles than for others.[32]

Conclusion

The findings of this study indicate that CFD simulations have significant potential to enhance surgical planning and predict outcomes in aortic surgery. However, effective application depends on adherence to specific principles and a clear understanding of their limitations. Our results suggest that CFD can reliably predict hemodynamic changes after surgery in 75% of cases, particularly in patients with relatively uncomplicated anatomical profiles and few complicating factors.

It is advisable to use CFD alongside traditional clinical assessments, advanced imaging techniques, and the surgeon's expertise. To further enhance predictive accuracy, CFD modeling should incorporate additional parameters, including tissue mechanical properties, inflammatory responses, and other patient-specific factors. Additionally, conducting longitudinal studies with larger sample sizes and extended follow-up periods will be crucial for validating this technology.

Ultimately, while CFD cannot entirely replace clinical judgment, it can provide vital insights for optimizing treatment strategies and minimizing postoperative complications. Future advancements should focus on developing more comprehensive models, enhancing validation methodologies, and integrating CFD more effectively into clinical decision support systems.

Ethical Considerations

This study received ethical approval from the Ethics Committee of Iran University of Medical Sciences, under the code IR.IUMS.FMD.REC.1403.342.

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